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SOLAR X-RAYS: SLOW VARIATIONS AND TRANSIENT EVENTS

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ABSTRACT

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Solar X-ray flux integrated over the interval 0.1 - 10 Å was measured from the OSO-1 satellite in early 1962 using a xenon-filled ion chamber with a thin beryllium window.

A slowly-varying component of X-ray flux was observed which correlates well with the slowly-varying component of 2800-Mc solar radiation, and which can be accounted for by localized sources having the same horizontal extent as Ca plages with thicknesses proportional to their diameter; and having an electron temperature of about $2.8(10)^6$ °K and an electron density of about $5(10)^9$ electrons per cm^3. A further conclusion is that for these conditions the ratio of line emission to continuum emission is at least 10:1 and more probably 30:1.

In addition to a slowly-varying component, transient events (X-ray flares) lasting from 10 minutes to a few hours were frequently observed. Correlations with H-α flares, with SID's, and with 2800-Mc transients have been investigated; the results show that as an indicator of local solar activity, the OSO-1 X-ray experiment was more sensitive by a large factor than indicators based on ionospheric effects or than indicators based on observations of solar flux in visible or radio wavelengths. X-ray flares were frequently observed to be associated in groups possessing a characteristic pattern; the implications are discussed.

AUTHOR

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1. INTRODUCTION

With the launching of the OSO-1 on March 7, 1962, it became possible for the first time to point instruments at the sun accurately and continuously for entire daylight portions of a satellite orbit; for the 550-Km orbit of OSO-1 these observing time intervals were the order of one hour each, separated by darkness intervals of about two-thirds of an hour. The observing periods were long enough to disclose some interesting dynamic effects which would be difficult to study otherwise.

2. SENSOR CHARACTERISTICS

OSO-1 provided coverage of the solar X-ray radiation near a wavelength of 10 Angstroms by means of an ion chamber whose characteristics are given in Table 1. The conversion efficiency as a function of wavelength is shown in Figure 1.

TABLE 1
Sensor Characteristics

Window Material	Beryllium
Window Thickness	0.005 inch
Total Window Area (Two chambers in parallel)	3.38 cm^2
Absorbing Gas	Xenon
Gas Pressure	780 mm
Ion Chamber Depth at Normal Incidence	2.19 cm
Ion pairs per erg	$2.8(10)^{10}$

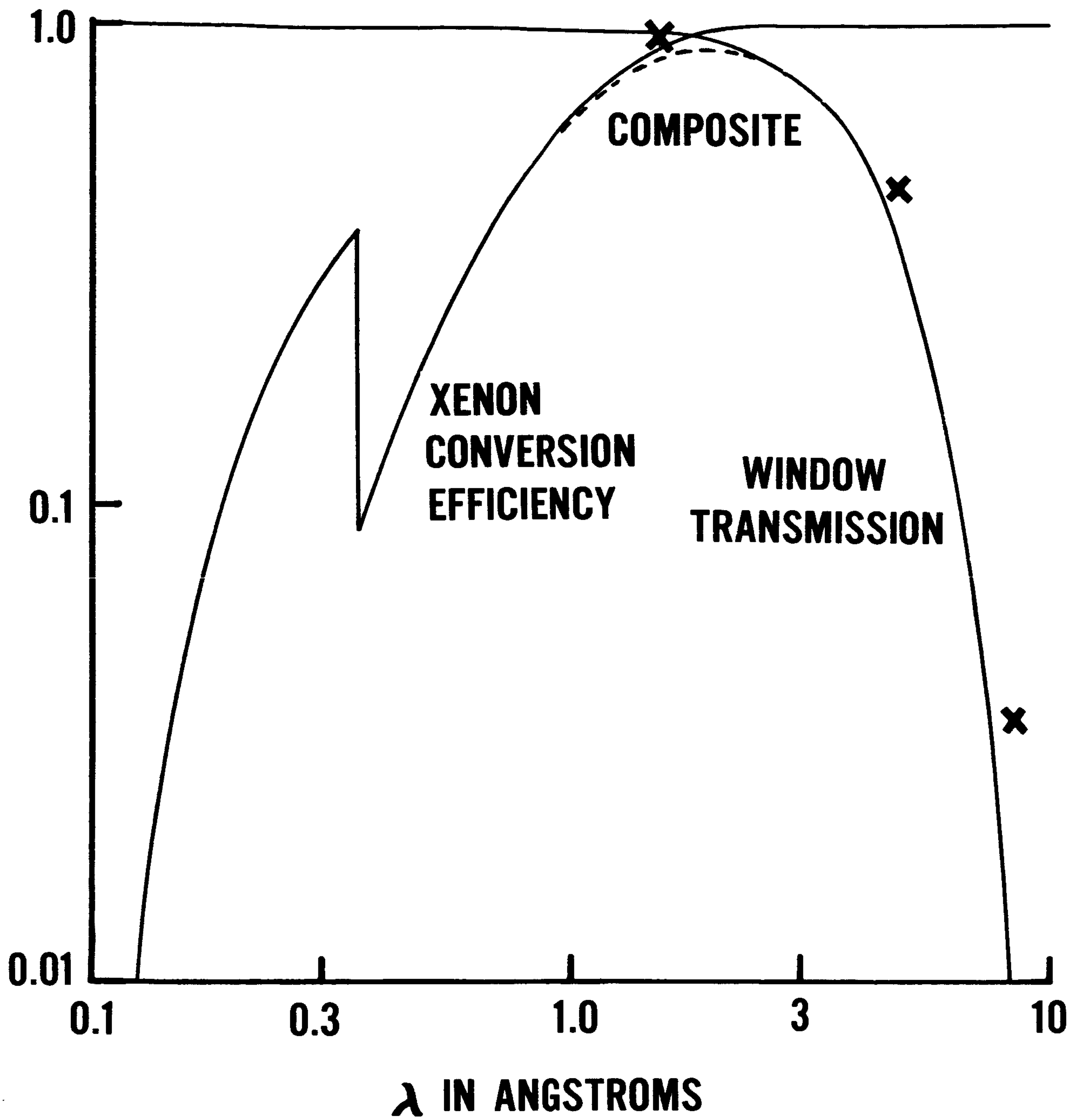

Figure 1 - OSO-1 Ion Chamber Conversion Efficiency
As Function of Wavelength - Theoretical
\+ Experimental

The full-scale sensitivity is, of course, dependent upon the shape of the input spectrum. It will be shown that for non-flare periods it is reasonable to assume a spectral shape consistent with a $2.8(10)^6$ $^{\circ}K$ plasma; for such a spectrum, wavelengths contributing to the output current lie in the interval 3 - 11 Å; the full-scale sensitivity at such times is $1.8(10)^{-3}$ $ergs \cdot cm^{-2} \cdot sec^{-1}$ within this wavelength region. For comparison with earlier measurements [1] over bandwidths specified as 2 - 8 Å, the full-scale sensitivity over such a band is $3.6(10)^{-4}$ $ergs \cdot cm^{-2} \cdot sec^{-1}$.

3. INPUT SPECTRUM ASSUMPTIONS

Both of the full-scale flux values mentioned above are computed for an input spectrum shape equivalent to a $2.8(10)^6$ $^{\circ}K$ plasma. The basis for this choice is threefold:

(1) A direct measurement of spectral shape between 7 and 11 Angstroms was made by Pounds, Willmore, et al [2] from the satellite Ariel on April 27, 1962, at 2110 UT, two hours prior to a small visible flare. The spectrum obtained by this group fits a $2.8(10)^6$ $^{\circ}K$ plasma; integrating their absolute flux values between 7 and 11 Å gives a value for the integral of $1.2(10)^{-3}$ $ergs \cdot cm^{-2} \cdot sec^{-1}$. At this time the OSO-1 X-ray ion-chamber experiment was off-scale, implying an integrated flux over the same wavelength interval (that is, 7 - 11 Å) of $\geq$ $1.7(10)^{-3}$ $ergs \cdot cm^{-2} \cdot sec^{-1}$, for the same spectral distribution. The agreement between OSO-1 and Ariel for the solar X-ray flux of April 27, 1962 is thus probably within a factor of 2.

(2) An assumed temperature appreciably less than $2.8(10)^6$ $^{\circ}K$ would require too high an electron density to produce the X-ray fluxes measured

by OSO-1. This statement is true either if the X-ray source is (a) spread uniformly over the entire corona or (b) localized in centers of activity. If one computes the continuum flux to be expected at these wavelengths from the entire solar corona (assumed isothermal at a somewhat lower temperature, say $2.4(10)^6$ °K) one finds that to produce the lowest flux value measured by OSO-1, the integral of the square of the electron density taken over the entire corona is $55.3(10)^{49}$. This value should be compared with the value of $4.6(10)^{49}$ obtained by Shklovskii [3] using the coronal model of Allen [4] , or with the value of $3(10)^{49}$ obtained by Elwert [5] , [6] . Thus the theoretical flux in the continuum for an isothermal corona with Allen's electron density profile at $2.4(10)^6$ °K falls short of the lowest value measured on OSO-1 by a factor of order 15. In fact, one must place the entire corona at a temperature in excess of $3.5(10)^6$ °K to meet the lowest OSO-1 flux using such an all-continuum model. If one allows the contribution from line emissions to exceed the flux from continuum emission by a factor of 15, the corona in its entirety would have to be at a temperature of about $2.4(10)^6$ °K; but this, remember, is for the lowest flux measured by OSO-1. For more than 50 percent of the time the OSO-1 flux exceeded this lowest value by at least a factor of 10.

(3) An assumed temperature appreciably greater than $2.8(10)^6$ °K would be inconsistent with concurrent OSO-1 observations of the Fe XV to Fe XVI ratio made by Neupert [7] .

4. SPATIAL DISTRIBUTION OF X-RAY SOURCES

From the fact that most of the time the measured flux from OSO-1 was much larger than the lowest value measured (which is already uncomfortably high for an isothermal corona with uniform density profile), we can only conclude that the previously observed spatial localization of sources of X-rays of somewhat longer wavelength must also exist for wavelengths less than 10 Angstroms, and inquire as to the conditions of temperature and electron density likely to be found in such local densifications. The observations of Billings [8] show that occasionally temperatures as high as $4.2(10)^6$ °K and electron densities as high as $2(10)^{10}$ cm^{-3} are found; more usual values [9] run $T_e < 3.5(10)^6$ °K and $n_e < 7(10)^9$ cm^{-3}.

5. SLOWLY-VARYING COMPONENT

A comparison of the slowly-varying part of the 10-Angstrom X-rays with 2800-Mc radiation confirms that the localized sources of solar X-rays are in some way associated with centers of activity such as Ca plages and/or sunspot groups. Figure 2 shows the time-history of both fluxes for about 2.5 solar rotations in the early life of OSO-1. It can be seen that the smoothed X-ray flux correlates fairly well with the excess 2800-Mc flux above a background of about 75 flux units appropriate for the "quiet" sun at that phase of the solar cycle [10].

The lowest X-ray flux measured by OSO-1 (on April 6, 1962) was: for $\lambda < 8$ Å, $3.6(10)^{-5}$ $erg \cdot cm^{-2} \cdot sec^{-1}$; for $\lambda < 11$ Å, $1.8(10)^{-4}$ $erg \cdot cm^{-2} \cdot sec^{-1}$. This may be considered an upper bound on the X-ray flux from the "quiet" sun. This flux occurred at a time when only 3 plages of area $\geq$ 1000 millionths of a solar hemisphere were visible on the disk. The nearest plage behind the west limb had set three days previously, and the nearest behind the

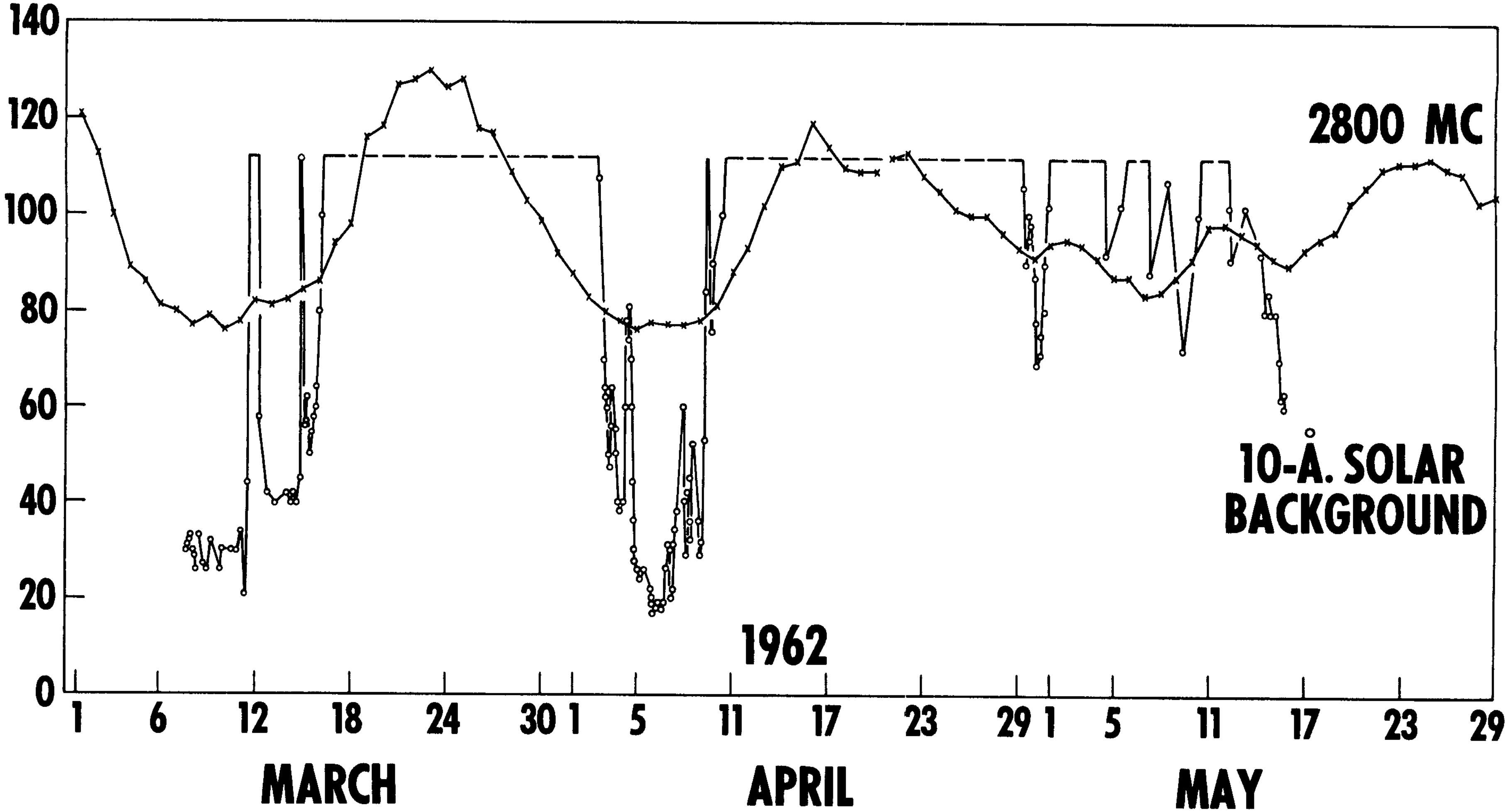

Figure 2 - Slowly-varying Components of 2800-Mc Solar Flux and of $\lambda <$ 11 Angstrom Solar X-rays

east limb was not to rise until 1.5 days later. If we now assume that the X-ray emission is coming from 3 "pillbox" volumes, one associated with each of the 3 plages, each having its base area equal to the plage area and furthermore having a height equal to 1/2 the diameter of its base, we have the situation shown in Table 2. Using the total source volume obtained

TABLE 2

Plages for 6 April, 1962

Observed Ca Plage		Assumed X-Ray Source		
McMath Plage No.	Area in millionths of solar hemisphere	Area cm^2	Height cm	Volume cm^3
6377	1600	$4.90(10)^{19}$	$3.95(10)^9$	$1.94(10)^{29}$
6378	1000	$3.06(10)^{19}$	$3.12(10)^9$	$0.954(10)^{29}$
6379	1000	$3.06(10)^{19}$	$3.12(10)^9$	$0.954(10)^{29}$

Total Volume = $3.85(10)^{29}$ cm^3

from Table 2, Table 3 gives the value of $\int n_e^2 \, dV$ required to fit the observed X-ray flux of 6 April 1962 for several assumed temperatures, and shows the resulting values of n_e for various assumptions regarding the relative contribution of line emission [6]. The volume above plage #6379 was observed by Billings [9] on 9 April 1962 to have a faint continuum enhancement from which he estimated $n_e = 0.5(10)^{10}$. If this was indeed the correct electron density, and if (as is most likely from such a weak source [9] the electron temperature was not greater than $3.0(10)^6$ °K, Table 3 indicates the ratio of line emission to continuum emission was at least 10:1. If T_e was no greater than the $2.8(10)^6$ - degree value obtained from the Ariel spectrum of April 27, the ratio of line emission to continuum emission must have been around 30:1.

TABLE 3

Electron Density for Plages of 6 April, 1962

T_e In million degrees K	$\int n_e^2 dV$ for April 6, 1962 if all continuum	n_e in units of 10^{10} electrons cm^{-3} Ratio of line emission to continuum 1:1	3:1	10:1	30:1
2.4	$55.3(10)^{49}$	2.68	1.90	1.14	0.68
3.0	$11.9(10)^{49}$	1.25	0.88	0.53	0.32
3.5	$4.9(10)^{49}$	0.80	0.56	0.34	0.20

6. X-RAY FLARES

Up to now we have discussed only the slowly-varying component of the X-ray emission: in addition to these quasi steady-state conditions, transient events (X-ray flares) lasting usually from 10 minutes to a couple of hours were frequently observed. Such an event is shown in Figure 3, and should be compared with the quiet period of similar duration

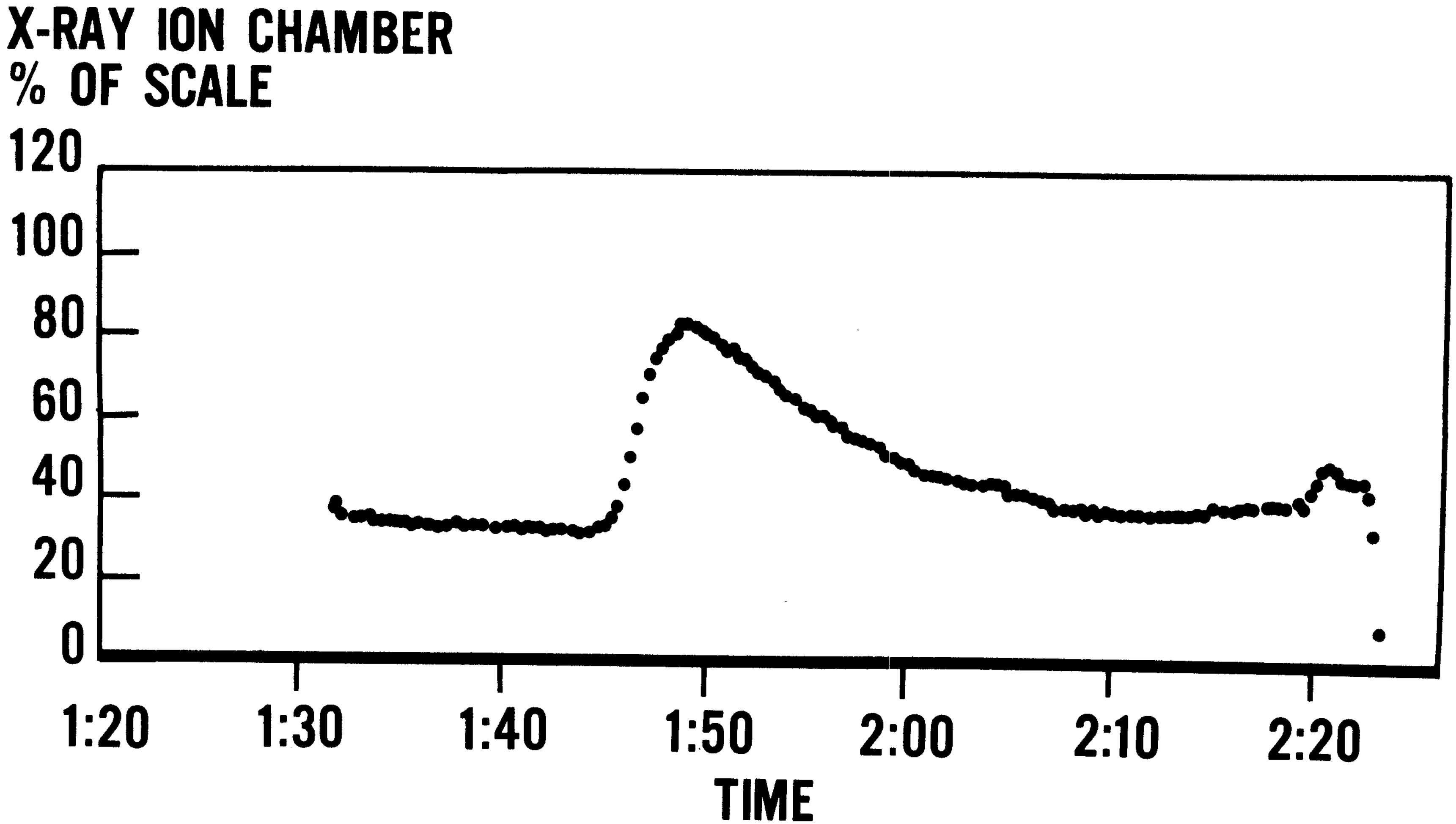

Figure 3. - Typical Small X-ray Flare

shown in Figure 4. The particular event of Figure 3 contains a total energy below 11 Å of $2(10)^{27}$ ergs.

6.1 Correlation with H-α Flares

During the 9-day interval between launch and March 16, 1962 (at which time the rising of plage #6370 on the east limb supplied enough X-ray emission to carry the experiment off-scale), approximately 60 X-ray flare events lasting from 10 minutes to 1 hour were seen, and 4 events were seen to last about 5 hours.

During this same interval (1620 UT March 7, 1962, to 1620 UT March 16, 1962) some 33 H-α flares were reported by ground-based observatories. Of these H-α flares, 6 would have been unobservable from OSO-1 for various reasons (satellite night, failure to command data storage readout, etc.). Of the remaining 27 H-α flares, 3 occurred while the X-ray experiment was still off-scale because of a previous large event. This leaves 24 H-α flares which can be tested for correlation with the X-ray flares. Of this group of 24, it appears that 11 correlate well, 3 definitely have no counterpart in X-rays, and the remaining 10 are doubtful because of insufficient data or an excessive time difference ($>$ 10 minutes). Conversely, there are 6 full-scale or greater X-ray events for which no H-α flare was reported even though observations were presumably being made at the time. Certainly more observations will be required before a definite statement can be made regarding a correlation or lack thereof between H-α flares and X-ray flares.

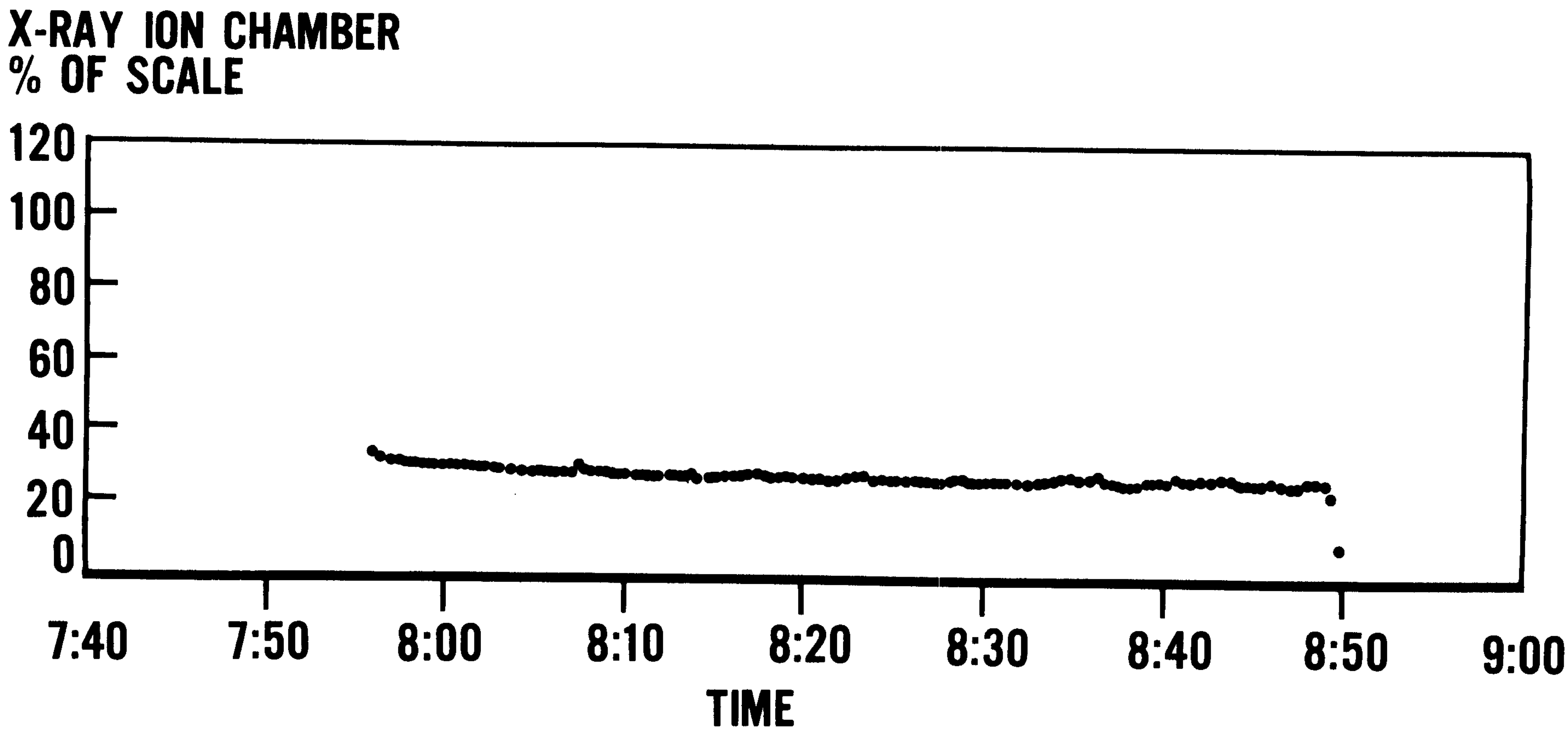

Figure 4 - Typical "Quiet" Period

6.2 Correlation With SID's

In looking for correlations with Sudden Ionospheric Disturbances, all X-ray events exceeding the full-scale saturation level were barely detectable (if observing conditions permitted) in Sudden Phase Anomaly data for VLF transmissions via the D layer. Only the large event of 13 March was seen in ionospheric indices other than SPA's.

6.3 Correlation With 2800-Mc Transients

Correlation with transients in the 2800-Mc solar flux is good; but again, full-scale X-ray events are represented by extremely small events (1 to 2 flux units) in the 2800-Mc data.

6.4 Grouping of X-ray Flares

Several apparent associations of certain X-ray flares into groups displaying a definite pattern were observed; Figure 5 shows such a grouping. Similar groupings are present in the data for the first week in April; in fact, the one particular March group shown in Figure 5 has an exact April counterpart 27.1 days later with identical time-separations between events and with identical peak excursions above mean background level. The envelope joining the peaks of the flares within a group is found:

(a) to be straight line, and

(b) to have the same slope (with either positive or negative sign) from group to group.

These characteristics of the flare groups indicate a constant time rate-of-change of X-ray source strength. Source strength is a function of electron density, of temperature, and of volume; furthermore, it is

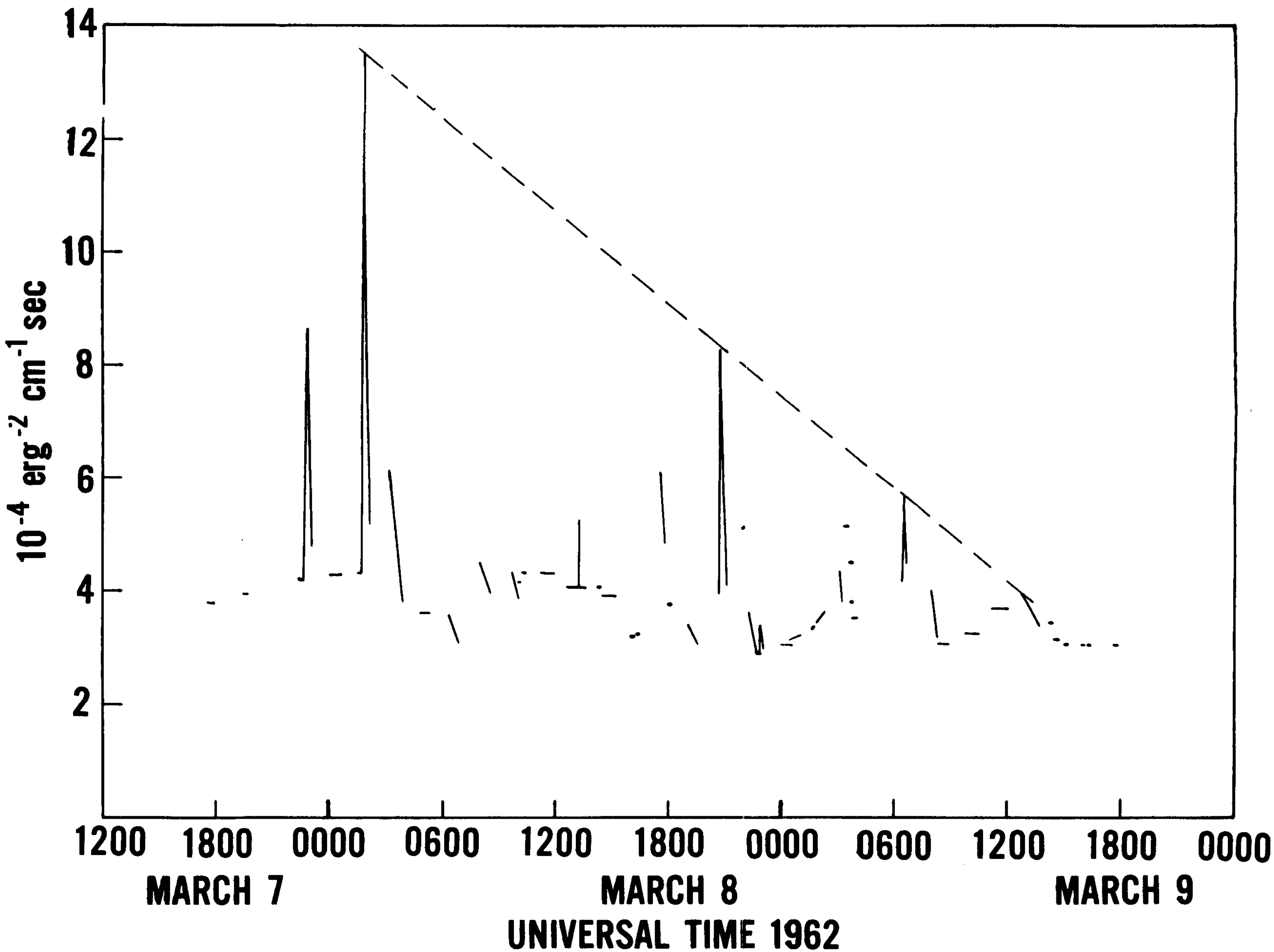

Figure 5 - Solar X-rays For $\lambda <$ 11 Å March 7 - March 9, 1962
Showing Grouping of X-ray Flares

difficult to see why any time-variation of either electron density or temperature would be of such a particular non-linear nature as to constrain the source strength to vary linearly with time. One is left with the concept of a volume which is either growing or diminishing at a constant rate, and which on occasion serves as a reservoir of high-temperature electrons and ions interacting to produce the X-ray flares.

7. SUMMARY

A slowly-varying component has been found in the solar X-ray flux below 11 Å which correlates with the slowly-varying component of the 2800-Mc solar radiation. A model for these quasi-stable X-ray sources which fits the OSO-1 data postulates localized sources having the same horizontal extent as Ca plages with thicknesses proportional to their diameter, and having an electron temperature of about $2.8(10)^6$ °K and an electron density of about $5(10)^9$ electrons per cm^3. For these conditions it is also necessary that the ratio of line emission to continuum emission be at least 10:1 and more probably 30:1.

In addition to a slowly-varying component, transient events (X-ray flares) lasting from 10 minutes to a few hours were frequently observed. Correlation with SID's and with 2800-Mc transients has been obtained; correlation has been attempted with H-α flares with somewhat ambiguous results. X-ray flares were frequently observed to be associated in groups possessing a characteristic pattern; the concept of a source volume varying linearly with time is invoked to account for the linear envelope of a flare group.

8. ACKNOWLEDGEMENTS

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